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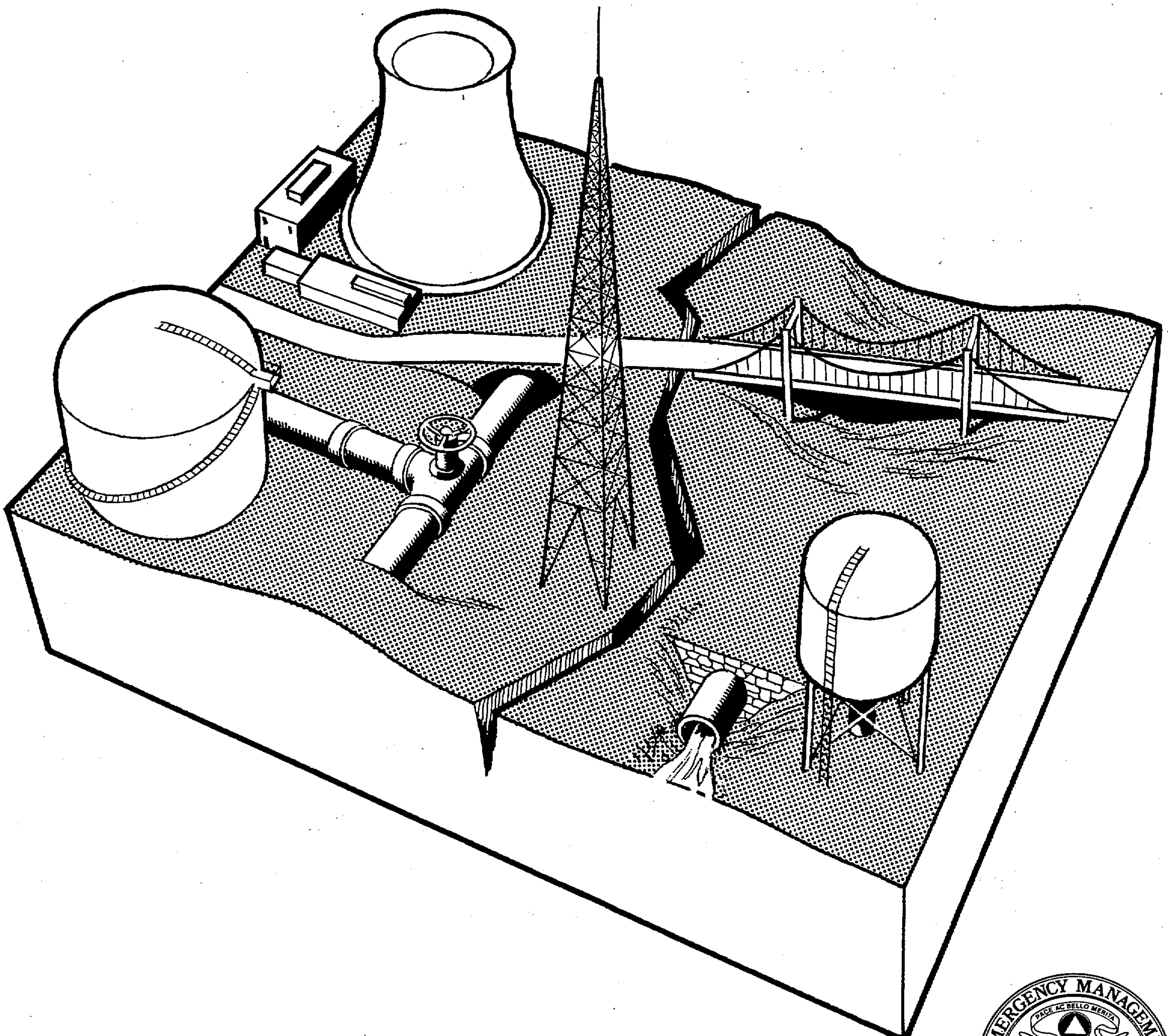
Earthquake Resistant Construction of Gas and Liquid Fuel Pipeline Systems Serving, or Regulated by, the Federal Government



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EARTHQUAKE RESISTANT CONSTRUCTION OF GAS AND LIQUID FUEL PIPELINE SYSTEMS SERVING, OR REGULATED BY, THE FEDERAL GOVERNMENT

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ABSTRACT

The vulnerability of gas and liquid fuel pipeline systems to damage in past earthquakes, as well as available standards and technologies that can protect these facilities against earthquake damage are reviewed. An overview is presented of measures taken by various Federal Agencies to protect pipeline systems under their jurisdiction against earthquake hazards. It is concluded that the overall performance of pipeline systems in past earthquakes was relatively good, however, older pipelines and above-ground storage tanks were damaged in many earthquakes. Modern, welded steel pipelines performed well, however, damage occurred in areas of major ground displacements. Available standards and regulations for gas pipelines do not contain seismic provisions. Standards and regulations for liquid fuel pipelines contain only general references to seismic loads. Standards and regulations for above-ground fuel storage tanks and for liquefied natural gas facilities contain explicit seismic design provisions. It is recommended that a guideline for earthquake resistant design of gas and liquid fuel pipeline systems be prepared for Federal Agencies to ensure a uniform approach to the protection of these systems.

Key Words: codes; earthquake engineering; fuel pipelines; lifelines; liquefied natural gas; natural gas; oil; oil storage; pipelines; seismic design; fuel storage tanks.

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DEFINITIONS

To assist the reader with the interpretation of terminology used in this report, a list of definitions is given below. Most of these definitions were taken from the Code of Federal Regulations, 49 CFR, Parts 192, 193, and 195 and from the technical literature. Some of the components of pipeline systems are also described in the text of the report.

- **Distribution line:** a pipeline other than a gathering or transmission line.
- **Gas:** natural gas, flammable gas, or gas which is toxic or corrosive.
- **Gathering line:** a pipeline that transports gas from a current production facility to a transmission line or main, or a pipeline 203 mm (8 in) in nominal diameter that transports petroleum from a production facility.
- **Liquefied natural gas (LNG):** natural gas or synthetic gas having methane (CH_4) as its major constituent which has been changed to a liquid or semisolid.
- **Liquid fuel:** crude oil and petroleum products.
- **Main:** a distribution line that serves as a common source of supply for more than one service line.
- **Pipe:** any pipe or tubing, usually cylindrical, used in the transportation of gas or liquid fuel, including pipe-type holders.
- **Pipeline:** any pipe or tubing, and associated joints, welds, couplings, tees, bends, and appurtenances, through which gas or liquid fuel move in transportation, excluding facilities to which the pipeline is connected, such as compressor units, metering stations, pumping stations, etc.
- **Pipeline facility:** new and existing pipelines, rights-of-way, and any equipment, facility, or building used in the transportation of gas or liquid fuels, or in the treatment of gas during the course of transportation.
- **Pipeline systems** (as defined in this report): all facilities and components that are needed for the transportation, distribution, and storage of natural gas, crude oil, and petroleum products.
- **Service line:** a distribution line that transports gas from a common source of supply to (a) a customer meter or the connection to a customer's piping, whichever is farther down stream, or (b) the connection to a customer's piping if there is no customer meter that measures the transfer of gas from an operator to a customer.
- **Storage tank:** a container for storing gas or liquid fuels, including an underground cavern.

- **Transmission line:** a pipeline through which gas and liquid fuels are transported from source areas to distribution points, processing plants, or storage areas.

- **Transportation of gas:** the gathering, transmission, or distribution of gas by pipeline, or the storage of gas, in or affecting interstate or foreign commerce.

LIST OF ACRONYMS

ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ANSI	American National Standards Institute
API	American Petroleum Institute
AWWA	American Water Works Association
BSSC	Building Seismic Safety Council
CFR	Code of Federal Regulations
CPUC	California Public Utility Commission
DOA	Department of Agriculture
DOD	Department of Defense
DOE	Department of Energy
DOI	Department of Interior
DOT	Department of Transportation
EERI	Earthquake Engineering Research Institute
EPA	Environmental Protection Agency
FEMA	Federal Emergency Management Agency
FERC	Federal Energy Regulatory Commission
FHWA	Federal Highway Administration
GLFL	Gas and Liquid Fuel Lifeline
GSA	General Services Administration
HUD	Department of Housing and Urban Development
LNG	Liquefied Natural Gas
LPG	Liquid Propane Gas
MMS	Minerals Management Service of DOI
NASA	National Aeronautics and Space Administration
NCEER	National Center for Earthquake Engineering Research
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NTSB	National Transportation Safety Board
OCS	Outer Continental Shelf
PGE	Pacific Gas and Electric Company
TCLEE	Technical Council on Lifeline Earthquake Engineering, ASCE
TRB	Transportation Research Board
TVA	Tennessee Valley Authority
UBC	Uniform Building Code
USGS	U.S. Geological Service of DOI

EXECUTIVE SUMMARY

The vulnerability of gas and liquid fuel pipeline systems to damage in past earthquakes, as well as available standards and technologies that can protect these facilities against earthquake damage are reviewed. Gas and liquid fuel pipeline systems considered include all facilities and components that are needed for the transportation, distribution, and storage of natural gas, crude oil, and petroleum products. An overview is presented of measures taken by various Federal Agencies to protect fuel pipeline systems under their jurisdiction against earthquake hazards.

It is concluded that the overall performance record of gas and liquid fuel pipeline systems in past earthquakes was relatively good. However, catastrophic failures did occur in many earthquakes, particularly in areas of unstable soils.

Modern, welded ductile steel pipelines, with adequate corrosion protection, have a good performance record. Failures that did occur were mostly caused by large, permanent soil displacements. Older pipelines, including welded pipelines built before 1950 in accordance with quality control standards less stringent than those used currently, as well as segmented cast iron pipelines, have been severely damaged. Some pipeline failures were attributable to the collapse of supporting structures to which they were attached.

Above-ground storage tanks, particularly those with large height-to-width ratios, were damaged in many earthquakes. Damage was caused by buckling and rupture of the shell, inadequate anchorage, excessive foundation settlements, inadequate flexibility of pipe connections, and contact of the sloshing liquid with the roof structure.

Pumping and compressor stations generally have performed well. Other above-ground support facilities, which were designed to resist earthquakes, suffered only limited structural damage. In many instances, however, problems were caused by inadequate tiedown of equipment and anchorage to the supporting foundations. Equipment outages were often caused by falling debris, collision with other items, sliding furniture and other objects, or failure of electrical supplies.

Fuel pipeline systems can be designed to be protected against most earthquake hazards. One of the most efficient and economical ways to obtain earthquake protection for new facilities is proper siting. Storage tanks and other above-ground facilities can normally be located to minimize exposure to unstable ground. Transmission and distribution pipelines traverse large areas and must often cross zones of potentially unstable soils. Nevertheless, careful planning in route selection, pipeline orientation, and location of critical components can promote good performance during earthquakes.

In addition to proper siting, pipeline systems can be designed to resist most, but not all potential earthquake loads and displacements. Criteria and guidelines for pipeline system design were presented by the American Society of Civil Engineers (ASCE, 1984). Criteria for tanks and other structures are incorporated in many existing standards. An effective protection against the environmental consequences of storage tank failures can be provided by secondary containment using earth dikes. Such secondary containments are presently required only for liquefied natural gas (LNG) storage facilities.

For existing facilities, retrofit and replacement of older facilities in critical areas should be considered. Methods for inspecting and retrofitting older pipelines are available.

Present standards for pipelines generally do not adequately address the earthquake problem. Neither the pipeline standards, nor the standards for oil storage tanks address the need for siting studies, even though such studies are often performed in practice. This deficiency could have adverse consequences, particularly in the Central and Eastern U.S., where the need for earthquake resistant design is not always fully recognized. There are also no secondary containment requirements for liquid fuel storage tanks, even if these tanks are located in environmentally sensitive areas. Standards and Federal regulations for LNG storage facilities contain siting criteria, secondary storage provisions and lateral force design requirements.

Three Federal Agencies have regulatory responsibilities for pipeline fuel transportation systems: The Department of Transportation (DOT) regulates oil and gas pipelines; the Federal Energy Regulatory Commission (FERC) regulates oil and gas pipelines and all LNG facilities, including terminal and storage facilities; and the Department of Interior's Minerals Management Service (MMS) regulates offshore production and transmission facilities. To some extent, the responsibilities of these agencies overlap. The review and approval of facilities by these agencies are based on the relevant provisions in the Code of Federal Regulations (CFR) and on engineering judgment. Explicit requirements for geological and seismological studies, secondary storage, and earthquake resistant design are included in the federal regulations for LNG facilities. The federal regulations for gas pipelines, as well as other standards referenced in these regulations, do not address earthquake resistant design. The federal regulations for liquid fuel pipelines have only a very general requirement for earthquake resistant design which is not sufficiently detailed or focused to provide direction on the critical aspects of seismic performance. Commercial standards, which address the earthquake resistant design for liquid fuel storage tanks, are adopted by reference.

Most other federal agencies do not own and operate pipeline systems (except for relatively short pipelines), but many agencies own distribution systems and storage facilities. Most agencies address the earthquake problem in some way, but there is no uniform approach to the protection of gas and liquid fuel pipeline systems against earthquake damage among agencies, and sometimes within agencies.

It is recommended that a guideline for earthquake resistant design of oil and liquid fuel pipeline systems be prepared for Federal Agencies to ensure a uniform approach to earthquake resistant practices by all Agencies. This guideline should adopt existing standards and regulations by reference, but add requirements for siting, and for secondary storage for some above-ground liquid fuel tanks.

Since the proposed federal guideline may eventually result in an updating of present federal regulations, close coordination between FEMA, DOT, FERC, and MMS, as well input from industry, will be required.

1. INTRODUCTION

As part of the Action Plan for the Abatement of Seismic Hazards to Lifelines (Building Seismic Safety Council, 1987), the National Institute of Standards and Technology (NIST) reviewed measures presently taken by Federal Agencies to protect gas and liquid fuel pipeline facilities against seismic hazards. This report summarizes the results of the study. The study deals with pipeline systems for oil, other petroleum products, and natural gas. Gas and liquid fuel pipeline systems consist of all facilities and components that are needed for the transforation, distribution, and storage of natural gas, crude oil, and petroleum products. The study does not deal with oil and natural gas production facilities, oil refining facilities, rail transmission, and pipeline transmission of coal slurries. A similar study has been conducted by NIST for electrical transmission and telecommunication facilities (Yokel, 1990)

All privately owned fuel transmission pipeline systems constructed in the U.S. must comply with Title 49, Transportation, Parts 190, 191, 192, 193, and 195 of the Code of Federal Regulations, (49 CFR, 1990) which deal with the transportation of natural and other gases, liquefied natural gas facilities, and the transportation of hazardous liquids by pipelines. This code provides minimum safety standards for gas and fuel transmission and storage facilities in the United States. While private industry must comply with the code, the provisions are not mandatory for Federally owned or operated lines.

Available data on earthquake damage of oil and gas pipeline systems and related facilities from the United States and many other countries indicate that earthquakes pose one of the major threats to pipeline operations, and their effects must therefore be adequately accounted for in the design process (ASCE, 1983).

Approximately one half of the nation's supplies of crude oil and petroleum products, and virtually all of its natural gas supplies, are transported through a network of 2.7 million kilometers (1.7 million miles) of pipelines (TRB, 1988). These pipelines provide a vital transportation service and extend over long distances and traverse a variety of different soil and geologic conditions, as well as regions with different seismicities. Thus, they are exposed to a wide range of ground conditions and behavior. Pipelines are interconnected with other pipelines, storage structures, and support facilities. Damage in one part of these complex systems can have important repercussions on the flow and serviceability in the other parts of the systems.

In the seismic design of buildings, bridges, and other structures above ground, inertial force is usually the most important factor to consider (Singhal & Benavides, 1983). Burial of pipelines tends in general to isolate them from the effects of inertial forces, but makes them susceptible to relative ground motions which cause distortions and strains (Hall, 1987). Large, permanent ground movements in the form of surface faulting, soil liquefaction, and landslides, are the most troublesome sources of damage to gas and liquid fuel pipelines (O'Rourke, 1987). A critical aspect of earthquake engineering for pipeline systems is understanding the properties of surrounding soils and the potential reactions of these soil deposits to earthquake excitation. This requires input from seismologists, geologists and geotechnical engineers which is not explicitly required in the Federal Regulations and not always provided in present practice.

Seismic damage to underground piping systems has been caused by fault displacements, landslides, liquefaction of sandy soils and associated lateral spreading and earthquake-induced settlements, differences in dynamic properties of two horizontally adjacent soil layers, and ground strains associated with traveling seismic waves. (Lee and Ariman, 1985, Ariman, 1987, O'Rourke, 1988, O'Rourke and Ayala, 1990).

Section 2 of this report contains a description of fuel pipeline systems and their components; the performance of fuel systems during past earthquakes is discussed in Section 3; Section 4 lists available standards, design guides, and earthquake damage mitigation technologies; Section 5 provides information on Federal practices; Section 6 contains conclusions and recommendations. Appendix A contains a summary of statements made by persons from various Federal Agencies and other organizations contacted in this study. A list of definitions is provided on page vii to assist the reader in the interpretation of terminology used in the report.

2. COMPONENTS OF NATURAL GAS AND LIQUID FUEL PIPELINE SYSTEMS

2.1 General Description

Natural gas and liquid fuels are conveyed through transmission pipelines from source areas to distribution points or processing plants. Gas and liquid fuel pipeline systems consist of all facilities and components that are needed for the transforation, distribution, and storage of natural gas, crude oil, and petroleum products. The major components of a typical natural gas production and transmission system are shown in the schematic drawing in figure 2.1 and in the plan of a specific system shown in figure 2.2. The components include pipelines, compressor stations, gas storage facilities, including underground storage fields, liquefied natural gas (LNG) storage facilities, and other storage facilities, LNG terminals, production and processing facilities, metering and control facilities, and distribution systems. Figure 2.3 is a schematic drawing of a petroleum transmission system, and figure 2.4 shows the layout of a particular U.S. pipeline system. Major components include, tank farms, oil field facilities, pumping stations, pipelines for crude oil and refined products, and monitoring systems. Gas and liquid fuel facilities include other components such as valves, regulators, communication and control systems, and maintenance facilities.

Control systems and communications are critical for safe and continuous conveyance of both gas and liquid fuels, and are vital for emergency response. They are also among the most vulnerable components of gas and liquid fuel facilities. Examples of critical components include monitoring instrumentation, communications equipment, computer hardware, remote valve controls, auxiliary equipment, emergency power systems, and uninterruptible power supplies (Nyman, 1991).

As an example of an automated monitoring and control system, an oil pipeline configuration in Florida, described by McPartland (1988), is shown in figure 2.5. This latter system is in an environmentally sensitive area and has a leak sensing system which will activate an alarm and effect an automatic shutdown when a leak is detected. It includes storage tanks, pumping stations, injection stations, booster stations, a port-dispatch station, check valves, generators, a control and monitoring system, and communication capabilities. Typical parameters that

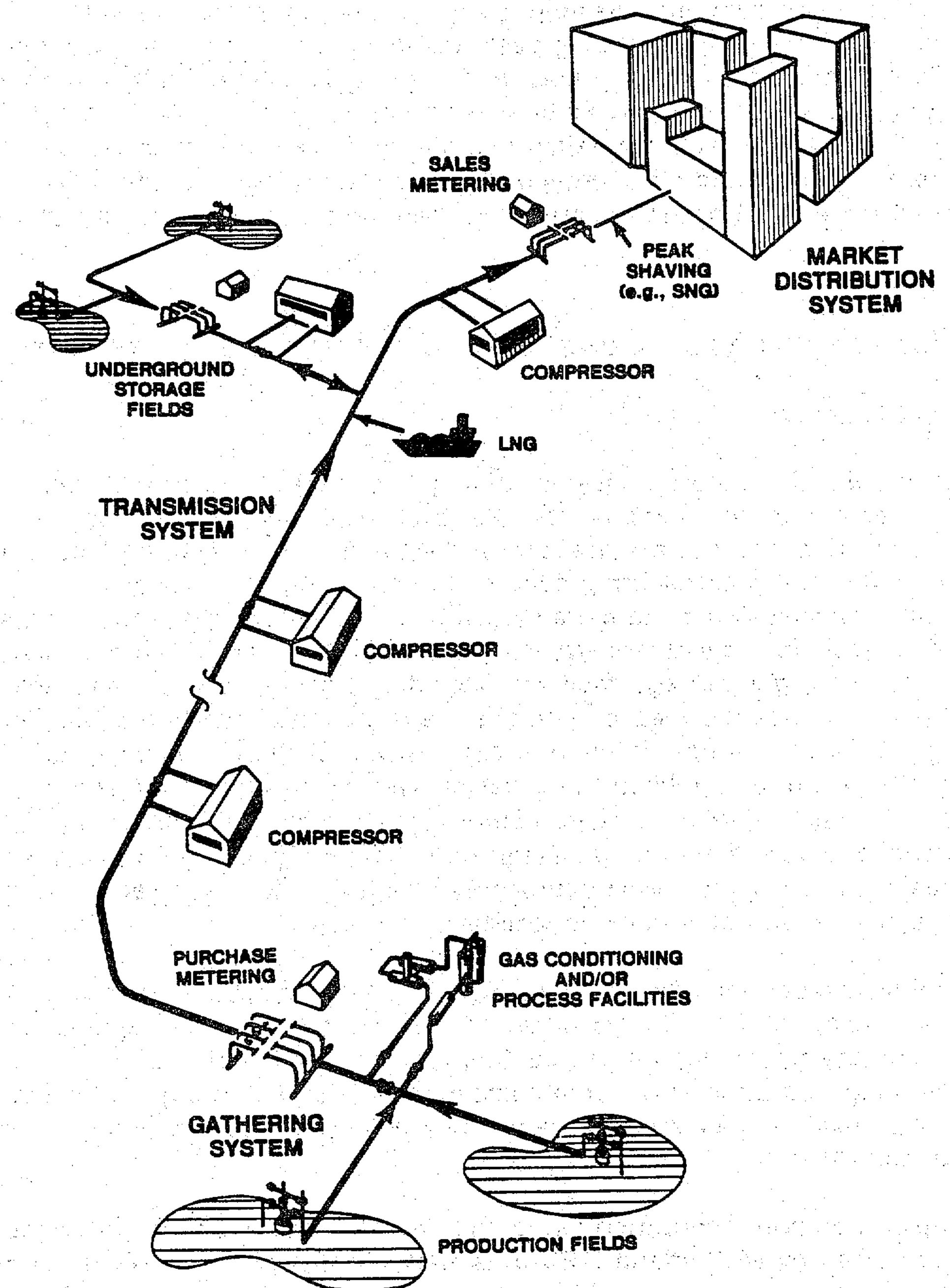

Figure 2.1 Schematic Drawing of Natural Gas Pipeline System (taken from National Petroleum Council, 1989)

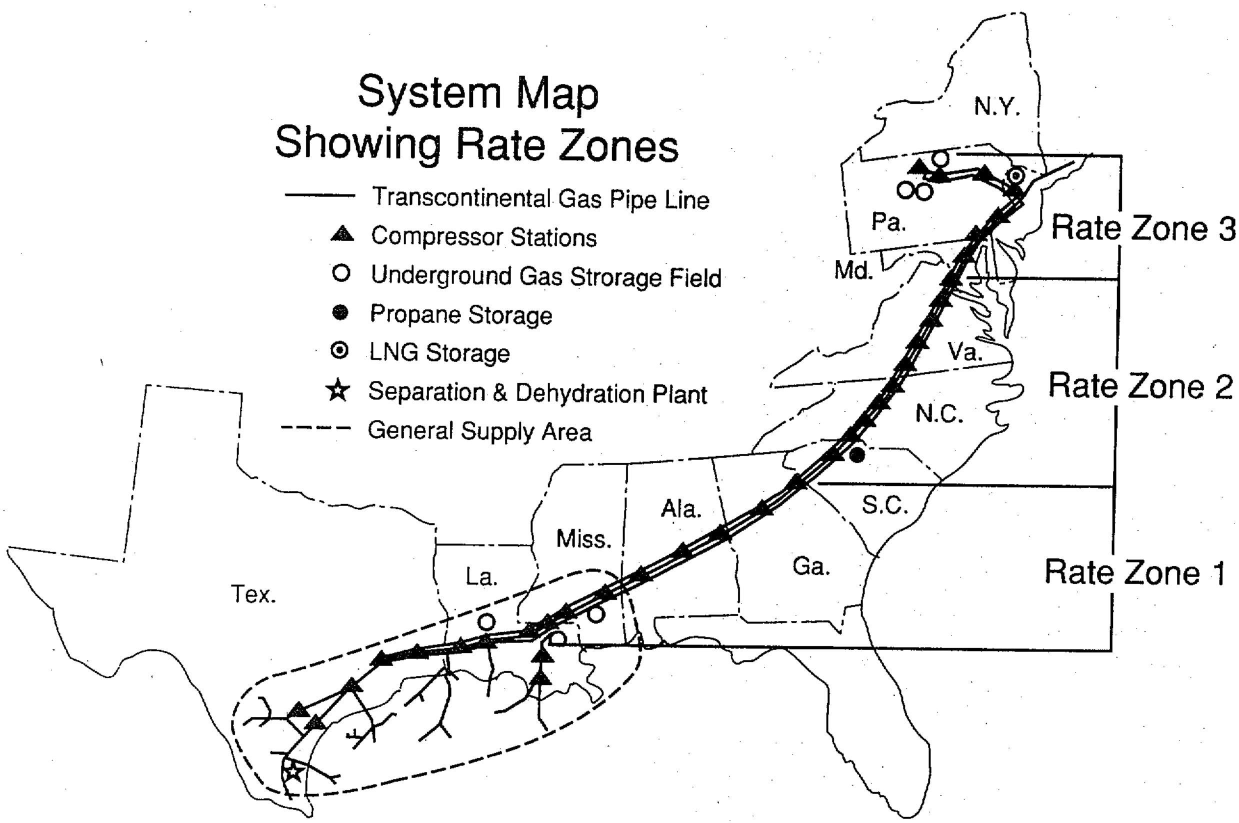

Figure 2.2 **Map of Gas Pipeline System in the Southeastern United States (provided by the American Gas Association).**

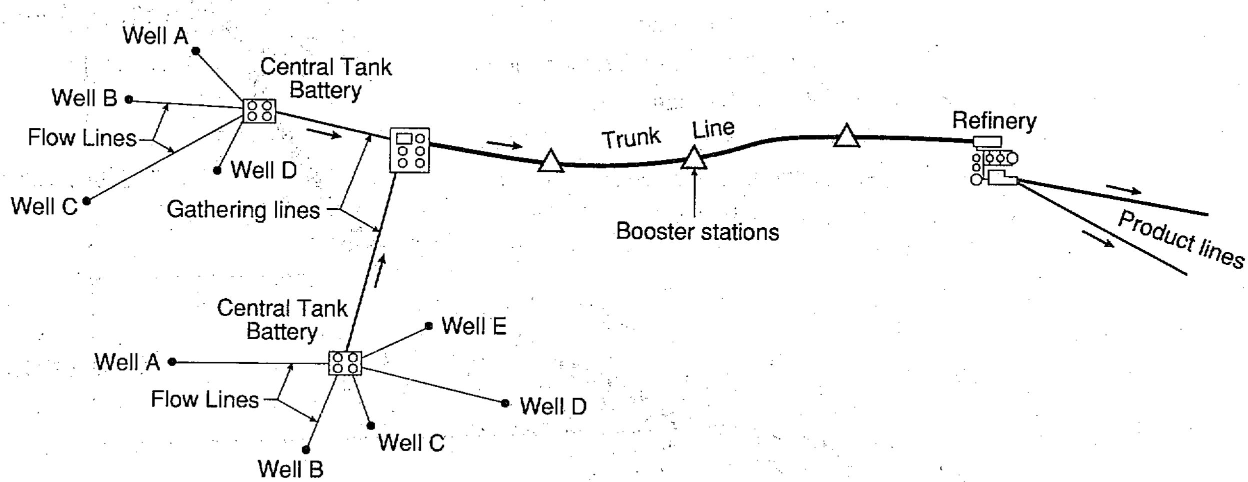

Figure 2.3 Schematic Drawing of Oil Pipeline System (taken in part from Giuliano, 1981).

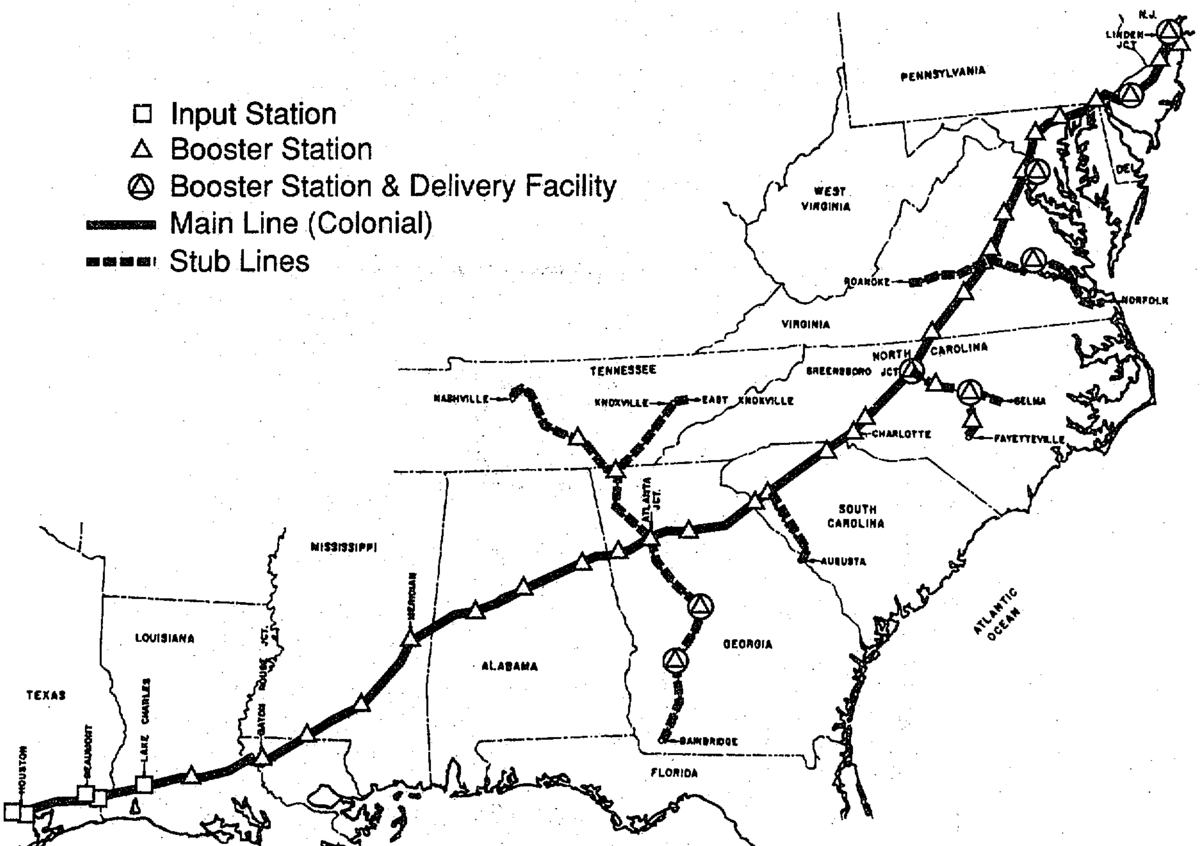

Figure 2.4 Map of Liquid Fuel Pipeline System in the Southeastern United States (taken from Giuliano, 1981).

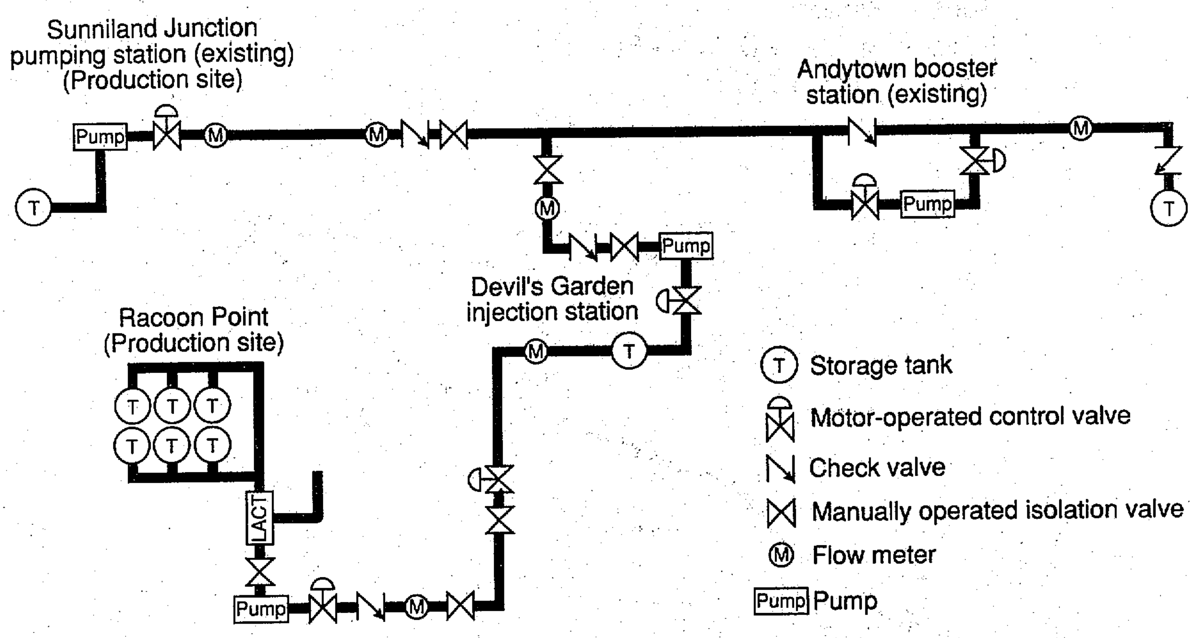

Figure 2.5 **Pipeline System with Leak Detection System and Automated Shutdown Controls (taken from McPartland, 1988).**

are measured to obtain information on the condition of a pipeline are pressure, flow rate, and linevolume balance. In certain situations, such as loss of pressure or failure of an operator to acknowledge a serious alarm within a preset time period, pipeline system shutdown is initiated automatically (Nyman, 1987). Natural gas systems require compressor stations and pressure regulators, and liquid fuel systems require pumping stations and sometimes heating and pressure reducing stations at intermediate locations.

According to Eguchi (1987), both gas and oil transmission systems should include isolation valves so that the effects of potential pipeline breaks can be confined to a relatively small portion of the system.

Because most pipelines have been constructed without special attention to seismic design, it is important that pipeline operations and maintenance programs begin to deal with potential earthquake damage and service interruptions (Nyman, 1987). McNorgan, 1973, reported that modern pipeline technology can provide earthquake resistant, but not earthquake proof structures.

2.2 Gas Pipeline Systems

2.2.1 Pipelines

Modern gas transmission pipelines are usually made of continuous girth-welded steel pipe and have diameters which range from 50 to 1060 mm (2 to 42 in), with most larger than 300 mm (10 in). These pipelines often carry internal pressures of 1.4 to 8.3 MPa (200 to 1,200 psi). Distribution pipelines have smaller diameters than transmission pipelines. The diameters of distribution pipelines are generally between 50 and 500 mm (2 and 20 in) and they may be composed of steel, cast iron, ductile iron, or plastic (EERI, 1986). Internal pressures in distribution pipelines generally range from 2 to 700 kPa (0.3 to 100 psi). Service pipelines have diameters generally less than 50 mm (2 in) and may consist of steel, copper, or plastic. Approximately 80 percent of all new distribution piping is made of plastic (EERI, 1986).

Hereafter are two examples of modern natural gas transmission facilities described in the literature. Fritsche, 1988, reported on a planned 238 km (148 mi) line in the state of Virginia. This line will include 43 km (27 mi) of 610 mm (24 in) pipeline near Leesburg, Virginia that will connect with the Virginia Natural Gas pipeline. This section of the pipeline will include a 10-MW (8,000-hp) compressor station and a measurement and regulating station. Design operating pressure of the line will be 6.9 MPa (1,000 psi) with actual delivery pressures of between 1.72 and 2.75 MPa (250 and 400 psi).

An example of a gas transmission system which includes liquefied natural gas (LNG) facilities and unloading terminals is given by Francis, 1984. He describes a natural gas transmission system operated by the British Gas Corporation, which includes compressor stations, LNG storage (above ground), LNG storage with a liquification plant (above ground), underground storage (salt cavity), and an exporting and reception terminal. There are about 120 installations in the U.K. national networks where gas is passed from national to regional control. These offtakes include compressor stations, storage facilities, and coastal terminals. Each of these offtake sites, and also some major junctions, are instrumented and the information telemetered to the data reduction computer at the regional center.

2.2.2 Compressor Stations

Compressor stations are generally located along a gas transmission line. Each station contains one or more centrifugal or reciprocating compressor units, and auxiliary equipment for purposes such as generating electricity, cooling discharge gas, and controlling the station (Tsal et al., 1986). It is possible to use two or more compressors at a station in parallel or in series.

Gas pipeline design discussed by Tsal et al (1986) involves: determination of the optimal number of compressor stations and their locations and design; and selection of the optimal pipe diameter and maximum allowable operating pressure. The following design variables need to be determined: number of compressor stations, compressor station locations, lengths of pipeline segments between compressor stations, diameters of pipeline segments, and suction and discharge pressures at each compressor station (Edgar et al., 1978).

2.3 Liquid Fuel Transmission Systems

2.3.1 Pipelines

Liquid fuel transmission pipelines often move large quantities of crude oil and petroleum products across active seismic regions. The Trans-Ecuadorian pipeline and the Trans-Alaskan pipeline are examples of major pipelines which transport oil across areas of high seismic activity (Anderson and Johnson, 1975). Anderson (1976), describes a crude oil pipeline system as consisting of three basic "segments". The primary segment is the line pipe that carries the crude oil. Piping associated with pump stations located along the length of the pipeline represents the second segment. The third segment is the piping associated with the tank terminal which is located at the end of the pipeline. All of these piping segments must be designed to resist forces developed during an earthquake. Pipelines may also be exposed to significant thermal forces and pressure forces which occur due to the flow of the oil and changes in direction. During operation, the pipeline is heated to a fairly constant temperature by the flow of oil in the pipe. Under operating conditions, the magnitude of the thermal forces is governed by the lowest temperature which occurred during installation of the pipeline.

Crude oil pipelines are usually buried below ground for economic, aesthetic, safety, and environmental reasons. In some instances, however, above ground support may be required, such as the Trans Alaskan pipeline, where structural support is needed to offset potentially large settlements caused by the melting of permafrost. Piping associated with a tank terminal is always located above ground (Anderson and Singh, 1976). Above ground support systems must allow movement due to thermal and pressure forces and also resist seismic forces. They offer the advantage of being readily accessible, either during normal operation or following a seismic disturbance. Above-ground pipeline systems are usually supported on gravel berms or pile bents.

An example of a buried pipeline, the Qinhuangdao-Beijing, China oil pipeline, which suffered some damage in the Tangshan earthquake, was described by Guan-Qing (1980). This oil pipeline went into operation in June 1975 and was 529 mm (20 in) in diameter, with a 7 mm (0.28 in) wall thickness, and was approximately 350 km (217 mi) long. The pipeline transported crude oil and was operated at a pressure of 5.9 MPa (856 psi) with the oil inlet temperature at 65 to 70° C (149 to 158° F). Along the pipeline length were two pump/heating stations and three heating stations. The pipeline was buried underground, except for river crossings, with 1.2 meter (47 in) cover. In most cases the pipeline was buried below freezing level and above the water table. The line used arc-spiral-welded steel pipe with a yield strength of 343 MPa (50 Ksi) and ultimate strength of 510 MPa (74 Ksi). The complete system was coated with reinforced asphalt and protected cathodically.

The Trans-Alaskan pipeline is 1230 mm (48 in) in diameter, with a wall thickness of 12 mm (0.462 in) or 14 mm (0.562 in). It is specially coated and cathodically protected from corrosion. It is 970 km (603 mi) long and crosses rivers and mountains, and reaches an elevation of 1460 m (4790 ft) (Factor and Grove, 1979). The line has eight pump stations. Slightly less than half of the pipeline is buried in stable soil. Above ground pipelines in areas of permafrost are insulated and jacketed with galvanized steel and mounted on crossbeams supported by vertical members set in the ground. The pipeline has 151 valves, including check valves to prevent a reversal of flow where oil is pumped uphill.

2.3.2 Pumping Stations

Friction loss associated with the flow of oil diminishes pressure in the pipeline. At certain intervals the pressure must be boosted by pump stations. Pumping is also required to transport oil uphill wherever this is required by topographic conditions. The spacing of these pump stations depends on the type of oil transported, the size of the pipe, and the topography. Pump station spacing generally ranges from 65 to 240 km.

2.3.3 Storage Tanks

Modern oil and liquid fuel storage tanks included in lifeline systems vary from 12 to 76 m (40 to 250 ft) in diameter with heights that are nearly always less than the diameter (Nyman, 1987). Ground supported tanks can be classified as anchored or unanchored tanks depending on their support conditions (Haroun, 1983). Most modern oil storage facilities use floating roof welded steel tanks (Kennedy, 1979).

Liquid fuel and gas storage tanks come in a variety of configurations. They may be elevated, ground supported, or partly buried. Ground supported, circular cylindrical tanks are more numerous than any other type because they are simple in design, efficient in resisting primary hydrostatic pressure, and can be easily constructed (Haroun, 1981).

3. PERFORMANCE OF GAS AND LIQUID FUEL PIPELINE SYSTEMS IN PAST EARTHQUAKES

Throughout the world, earthquakes have caused significant damage to underground pipelines, oil storage tanks, and some pump facilities (Eguchi, 1987). For above-ground components of pipeline systems, such as buildings and storage tanks, inertial forces resulting from ground shaking are a major concern. For buried pipelines, inertial forces are of little concern, but faulting, landslides, and liquefaction pose major problems (Hall, 1987).

3.1 Pipelines

3.1.1 Earthquake Effects

Ground deformations and displacements, rather than inertial forces caused by ground accelerations are the major cause of earthquake damage to pipelines. Ground deformations can be viewed as falling into two categories: ground strains caused by seismic wave propagation which do not result in large permanent deformations; and ground displacements caused by faults, soil liquefaction, settlements, and landslides. In addition to ground deformations, pipelines can also be damaged by secondary earthquake effects, such as failure of adjacent or connected structures, flooding, explosions and fires, and failure of support facilities.

3.1.1.1 Traveling Ground Waves

Hall reported in 1987 that there was no case of a modern buried welded steel pipeline failure attributable to ground shaking. However, one documented case of traveling ground wave damage to a corrosion-free modern continuous steel pipeline occurred to a 1067-mm (42-in) line during the 1985 Michoacan earthquake (O'Rourke and Ayala, 1990).

In other cases, pipeline damage from traveling ground waves has been observed in natural gas pipelines which were weakened either by corrosion or welds of poor quality (EERI, 1986). Recent Mexico City and Whittier, California earthquakes have shown that buried water pipelines were apparently damaged solely by seismic shaking effects since no large fault movement or soil liquefaction was found in either of the cities after the earthquakes (Wang, 1988). According to Wang, damage occurred mostly in regions of discontinuities in subsurface conditions. O'Rourke and Ayala, 1990, also reported cases in the 1964 Puget Sound, 1969 Santa Rosa, and 1983 Coalinga earthquakes where the sole damage mechanism appeared to be seismic wave propagation which did not result in permanent ground displacements.

3.1.1.2 Permanent Ground Displacements

Large permanent ground movements caused by surface faulting, soil liquefaction, and landslides are the most troublesome sources of earthquake damage to gas and liquid fuel pipelines (O'Rourke, 1987, EERI, 1986, Guan-Qing, 1980, Anderson, 1985, O'Rourke and Trautmann, 1981). Therefore, a primary concern for buried pipelines is their ability to accommodate abrupt ground distortions or differential displacements (ASCE, 1984). The amount and type of ground displacement across a fault or fault zone is one of the most important factors to be considered in the seismic design of pipelines crossing active faults (ASCE, 1983). Since ground displacements are in most cases difficult to predict, it is also difficult to develop designs which will protect pipelines against their effects. The most common forms of ground displacements are faulting, lateral spreading caused by liquefaction, and slope failures (landslides).

Pipelines that can otherwise sustain strong levels of shaking can be damaged severely by ground failures and local concentrations of movement (O'Rourke and Trautmann, 1981). Evidence reported in the literature indicates that underground pipelines perform worse in areas experiencing significant permanent displacement or ground failure (Eguchi, 1987, Lee and Ariman, 1985). It was pointed out that evidence from the 1906 San Francisco, 1952 Kern County, 1964 Niigata, 1964 Alaska, 1971 San Fernando, 1978 Miyagi-ken-oki, and 1983 Nihonkai-Chuba earthquakes shows an unmistakable correlation between permanent ground displacement and buried pipeline damage (O'Rourke, 1987, EERI, 1986). Ariman, 1984, noted from detailed examination of records from the 1971 San Fernando earthquake that strong and ductile steel pipelines withstood ground shaking but were unable to resist the large permanent ground deformation generated by faulting and ground failures.

During the 1971 San Fernando earthquake the steel pipeline system resisted significant seismic forces and the natural gas piping system failed primarily at or adjacent to locations where there were sharp vertical or lateral dislocations or ground ruptures (ASCE, 1984). The pipe was torn or twisted apart at these locations, and the breaks were in the body of pipe, at fittings or at welds, whichever existed at these ground displacement points. At locations where there was severe ground displacement but no ground ruptures, the piping yielded but did not break. O'Rourke and Tawfik, 1983, reported on the effects of lateral spreading on buried pipelines during the San Fernando earthquake. Lateral spreading led to severe damage in this earthquake (EERI, 1986, O'Rourke and Trautmann, 1981, O'Rourke, 1988). Eleven transmission pipelines were affected by lateral spreading and liquefaction-induced landslides. Five pipelines were damaged substantially. The most severe damage occurred in gas transmission pipelines that were deformed by lateral spreading along San Fernando Road, where differential lateral movements as large as 1.7m (5.6ft) were observed. Ground movements due to seismic liquefaction can be extremely large and of great detriment to pipeline safety (Darragh, 1983).

With regard to pipeline failures in liquefied areas, during the 1964 Niigata earthquake the average failure ratio for pipes 100-300mm (4 to 12in) diameter was about 0.97 per km (Katayama et al., 1975). Failure types were reported to be pipe and weld breaks, and joint separations.

3.1.1.3 Secondary Effects

Pipelines have been damaged or destroyed at particular locations due to secondary effects of earthquakes. These secondary effects include flooding caused by failure of water conduits, reservoirs, and dams; hazards from fallen power lines; and explosion hazards when oil tanks and gas lines are ruptured. Experience from past earthquakes indicates that bridges and other supporting facilities can have a significant effect on the performance of oil and gas pipeline systems. An example of secondary damage to pipelines is a pipeline mounted on a bridge that was totally destroyed during the 1976 Tangshan, China earthquake. The bridge length was about 800m (2625ft) and the earthquake intensity was reported to be 9 at this location (Guan-Qing, 1980). Some secondary hazards may be mitigated most effectively through proper siting practices and design of components (Ward, 1990). Design criteria for oil and gas pipeline systems should account directly or indirectly for failure of facilities which may affect the performance of the oil and gas pipeline systems (ASCE, 1983). It is noted that pipeline river crossings can be accomplished by directionally controlled horizontal drilling techniques (Hair and Hair, 1988) which provide an opportunity to avoid deposits susceptible to liquefaction and ground instability by selection of launching and receiving areas and appropriate drilling depths.

3.1.2 Factors Affecting Performance of Pipelines

During past earthquakes the performance of large-diameter oil and gas continuously-welded ductile steel pipelines, with modern quality welds and corrosion protection, has been for the most part satisfactory (Nyman and Kennedy, 1987, ASCE, 1984, ASCE, 1983, EERI, 1986, NOAA, 1973, O'Rourke and Ayala, 1990 ,O'Rourke, 1989). Also, no damage was reported to an apparently well constructed 500-mm (20-in) diameter steel transmission line during the 1989 Armenia earthquake (Schiff, 1989). Further evidence that modern buried welded ductile steel pipelines, which are properly designed, manufactured and installed, generally have performed satisfactorily and have not been ruptured by ground shaking is given by Ford, 1988, Wang, 1988, Lee and Ariman, 1985 , Anderson, 1985, Ariman, 1983, Singhal, 1983, and, Kennedy, 1979. Wave propagation damage to a modern welded steel pipeline is unusual (O'Rourke and Ayala, 1990, O'Rourke, 1988). Many large diameter oil and gas transmission pipelines located in seismic regions have gone through moderately large earthquakes, and their performance has been generally satisfactory.

Modern pipelines are made of ductile steel with full penetration welds, resulting in a system with substantial, inherent ductility (Nyman and Kennedy, 1987, Kennedy et al., 1979). Continuous piping systems must rely upon elastic-plastic properties of the pipe materials to allow enough yielding to prevent rupture or failure during earth movement (Ford, 1983). Because of this ductile behavior, it is expected that buried pipelines generally can withstand considerable soil distortion or differential displacement in cohesive or granular soils without rupture. It is well recognized that toughness (strength and ductility) and flexibility of both pipes and joints are the two governing factors related to the seismic performance of buried pipes (Kubo, 1979). On the basis of damage to gas transmission lines from the San Fernando earthquake, Ariman, 1977, concluded that ductility is the most important factor for seismic design of underground piping systems.

Extensive damage occurred to underground welded-steel transmission pipelines during the 1971 San Fernando earthquake (NOAA, 1973). The most serious damage occurred to an oxy-acetylene-welded pipeline installed about 1930. In the same general area of the San Fernando Valley that experienced extensive ground failures, several newer pipelines installed after 1960 did not experience failure. Before the early 1930s, steel pipelines in California were often constructed under quality control less stringent than that imposed today (EERI, 1986). The newer pipelines were characterized by higher yield strengths (x-grade) and modern arc welding (Eguchi, 1987).

Damage to welded steel pipelines during the 1952 Kern County earthquakes was reported to be more extensive with oxy-acetylene-welded lines than those with electric arc welds. The apparently higher incidence of earthquake damage for oxy-acetylene welds may be related to weld quality (EERI, 1986, McCaffrey and O'Rourke, 1983). Most of the damage to gas lines during the 1971 San Fernando earthquake was caused by tensile failures across oxy-acetylene welded joints. It was unlikely that these failures were related to the type of weld, but rather to the quality of the welds (McCaffrey and O'Rourke, 1983). The quality of the welds is one of the most important factors affecting the earthquake performance of pipelines.

It was reported that damage to gas transmission lines resulting from the 1971 San Fernando earthquake was concentrated in four pre-1931 lines that ranged from 300 to 660 mm (12 to 26 in) in diameter (Nyman, 1987, Johnson, 1983, NOAA, 1973). Most of the breaks were at the welds, but a number occurred between welds (EERI, 1986, Johnson, 1983, McNorgan, 1973, Bagwell, 1973).

Another example of increased number of breaks of oxy-acetylene-welded steel pipes compared to arc-welded steel pipes occurred during the 1964 Niigata earthquake. The average number of breaks of the oxyacetylene-welded steel pipes was five times greater than that experienced by normal arc-welded steel pipe (Eguchi, 1987).

The joints of cast-iron pipe have also been susceptible to damage by earthquake. In the 1923 Kanto earthquake over 4000 pipeline breaks were reported in the Tokyo region. Most of the damage occurred at the joints of small diameter cast-iron pipe which were pulled apart by the earthquake (Eguchi, 1987). Evidence from two major earthquakes in China (1975 Haicheng and 1976 Tangshan) indicate that pipe joints or pipeline portions near them were easily broken, either pulled out, crushed, bent, or sheared into two or many parts, while flexible joints were seldom damaged (Fu-Lu, 1983). For segmented pipelines the adoption of flexible joints with a rubber ring is the best way to reduce the damage (Shoaping, 1983).

Corrosion of pipes and pipelines affects their service life and reduces their ability to resist seismic forces (Ogawa, 1983). Isenberg, 1979, reported that more than half of the leaks in water pipelines attributed to the 1971 San Fernando, 1969 Santa Rosa, and 1965 Seattle earthquakes were in pipes weakened by corrosion. Experience in the petroleum industry indicates that steel pipe can be protected against external corrosion by a combination of coatings and cathodic protection (Hair and Hair, 1988). Corrosion of pipes and welded steel pipelines and methods for protecting them from corrosion are discussed by Isenberg, 1979, and O'Rourke et al., 1985. Pressure surge in pipelines due to seismic excitation may also increase the possibility of failure of pipelines weakened by corrosion (Young and Pardon, 1983, Ogawa, 1983).

3.1.3 Failure Mechanisms

The principal modes of failure for continuous, welded pipelines are direct tensile rupture, beam or local buckling, and excessive bending. For jointed or segmented pipelines, the principal modes of failure include rupture or excessive deformation of individual pipe segments, pull-out or compressive battering of joints, and excessive rotation of joints. There has been substantial research regarding the modes of pipeline failure (e.g., ASCE, 1984; O'Rourke, el al., 1985; O'Rourke, 1988), and all failure modes have been observed in previous earthquakes (e.g., Wang and O'Rourke, 1978; ASCE, 1984 Hall and O'Rourke, 1991), particularly in areas subjected to large permanent ground deformation.

The tensile capacity of a segmented pipeline is generally controlled by the tensile strength or operable pull-out displacement that characterizes the joints. For girth welded steel pipelines, tensile capacity depends on the amount of axial elongation which can be sustained until pipe rupture. Many modern steels have good post-yield characteristics in axial tension. Kennedy, et al. (1977) recommended a maximum strain of one-third the ultimate tensile capacity of pipeline steel for the combined action of axial and bending deformation. Typically, the direct tensile strain capacity ranges from 2 to 5 % for X-grade steels (ASCE, 1984).

Pipelines oriented to sustain tensile elongation in response to permanent ground deformation are able to accommodate relatively large ground displacement by virtue of the ductility of the pipeline steel. This principle is an underlying factor in the recommended design practices for pipelines crossing active faults (ASCE, 1984). Pipelines oriented to accommodate ground movement by means of combined axial tension and bending have performed well under liquefaction-induced lateral spreading. During the 1971 San Fernando earthquake, four large gas and liquid fuel pipelines located on the western side of the Upper Van Norman Reservoir were able to sustain approximately 2.5m (8.2ft) of lateral soil displacement which was directed perpendicular to the longitudinal axes of the lines (O'Rourke, et al., 1990).

Large compressive ground deformation can result in beam buckling, when the pipeline lifts out of the ground, or in local buckling or shell wrinkling, characterized by crippling and distortion of the pipe wall. Experimental results have shown that local wrinkling will begin at strains approximately 15 to 20% of the wall thickness to radius ratio of the pipe (ASCE, 1984). Strains on the order of 4 to 6 times as great generally can be sustained without tearing at a compressive wrinkle (Hall and O'Rourke, 1991). The opportunity for beam buckling is closely related to the depth of cover. For pipeline burial exceeding 0.5 to 1.0m (1.6 to 3.2ft), beam buckling generally will not occur so that only local wrinkling will result under these conditions from excessive compressive strains (Meyersohn and O'Rourke, 1991).

The most probable causes of large compressive strains in buried pipelines that can lead to buckling are fault movement (including creep), landslides and other massive ground movements. Experience has shown that pipelines with bends, elbows, and local eccentricities will concentrate deformation at these features, especially if ground movements develop compressive strains (EERI, 1986). It was observed in a number of sections of 406-mm (16-in) pipe that buckling under compressive forces at fault crossings occurred during the 1971 San Fernando earthquake (Ariman, 1983, 1984). Ring type buckling occurred to a 529-mm (21-in) diameter oil pipeline during the 1976 Tangshan earthquake. Its diameter was reduced by 40 percent. It should be noted that pipeline performance during the 1971 San Fernando earthquake indicated that local compressive forces can be imposed by reverse faulting despite a favorable orientation of the pipeline (McCaffrey and O'Rourke,1983).

The 1971 San Fernando earthquake caused significant damage to underground gas distribution pipelines. Most of these failures occurred at the welds of welded-steel pipelines with gas-welded joints. Pipeline ruptures at welds made before 1930 led to explosions which left craterlike depressions in residential streets (EERI, 1986). After the 1989 Loma Prieta earthquake, gas distribution system failures in the Bay and epicentral areas showed a significant potential for fires. These failures were predominantly in areas of unstable soils (NIST, 1990).

Seismic failure modes of buried pipelines in liquefiable zones were found to be pull-out, breaking, buckling, and crushing (Yeh and Wang, 1985). A state-of-the-art review of the behavior and damage of buried pipelines due to seismic excitation is presented by Mashaly and Datta, 1983.

3.1.4 Remedial Measures

Modern pipeline steels generally can accommodate average tensile strains on the order of 2 to 5 percent without rupture, with local strains of 15 percent or more. In Japan, steel pipes are allowed to have a design strain of 0.3% for a rare earthquake (Singhal, 1983-III). A reasonable criterion, suggested by Hall and Newmark, 1978, for permissible deformation to avoid rupture appears to be in the order of 1 to 2% strain in modern steel pipe at any section. Careful quality control over pipeline manufacture and welding is a necessity for achieving the desired performance under these strains (Nyman and Kennedy, 1987).

Damage to pipelines may be minimized provided that a correct choice of pipe material, type of joints, arrangement of the network, length of segments, location and details of fittings and accessories are made, and as long as pipelines are not located in the vicinity of fault or landslide zones (Fu-Lu, 1983).

Past earthquake fires in Japan have led to the installation of peak acceleration detectors at various locations in gas transmission lines (Schiff et al., 1984). Detection of certain levels of peak acceleration will reduce the pressure in the lines and isolate LPG storage tanks. Higher detected levels of acceleration will stop gas generation and valves to the transmission line are closed so that the system is sectionalized. Very high accelerations will result in purging of gas transmission lines. It is noted, however, that in 1973 McNorgan stated that the installation of earthquake, vibration, or automatic shut-off valves is not a panacea for such situations; such valves could cause severe problems from an operational standpoint.

3.1.5 Summary

With respect to buried gas and liquid fuel pipeline systems, the following lessons learned were summarized by the Earthquake Engineering Research Institute (EERI, 1986):

- Large permanent ground movements are the most severe earthquake hazard affecting gas and liquid fuel lifelines.
- Locations most vulnerable to earthquake damage are pipeline bends, elbows, tees, and local eccentricities, especially if compressive strains develop as a result of permanent ground movement.

- Pipelines made of steel with quality welds and protected against corrosion have performed well during earthquakes even when subjected to permanent differential ground movements.

- Some steel pipelines constructed before or during the 1930's are susceptible to earthquake damage because of relatively weak welds.

3.2 Tanks

3.2.1 Overall Performance Record

During previous earthquakes, many tanks have been damaged by strong ground shaking and some have failed with serious consequences. Because of the wide use of tanks and their vulnerability to earthquakes, many incidents of damage to tanks have been reported (EERI, 1986). During the 1964 Niigata earth quake, oil from ruptured tanks caught fire, damaging two refineries (ASCE, 1984). Waterways were polluted because of oil storage tank failure during the 1978 Miyagi-ken-oki earthquake (ASCE, 1984). Tank damage after the 1989 Loma Prieta earthquake was observed in the epicentral area, and as far as 120km (78mi.) from the epicenter (EERI, 1990). Because of numerous earthquake-induced failures coupled with the potential for fire, pollution, and contamination of surrounding areas, the seismic behavior of liquid storage tanks is a matter of great concern.

3.2.2 Earthquake Effects Causing Failures of Tanks

The predominant hazards for tank farms are ground shaking and liquefaction (Kennedy et al.,1979). Generally tank farms can be sited to avoid or minimize the potential damage associated with fault movement. In the 1964 Alaska earthquake, considerable damage to oil storage tanks occurred over a wide area of Alaska (Eguchi, 1987, ASCE, 1987). Much of the damage was due to the effects of tsunamis, earth settlement, and liquefaction. Eguchi, 1987, reported that experiences from this earthquake have led to significant changes in the design of above-ground storage tanks to resist earthquake forces.

3.2.3 Factors Affecting Tank Performance

Haroun, 1983, reported that tanks with large liquid depth-to-radius ratios frequently suffered structural damage, while shell damage was less common in large capacity tanks which have a large radius and a small depth-to-radius ratio. Overturning moments appear to have been of critical importance in tanks damaged during earthquakes. Seismic excitations produce hydrodynamic pressure at the liquid-shell interface resulting in a lateral force and overturning moment at the base of the tank. There were many reports of tank damage resulting from the 1989 Loma Prieta earthquake. Much of the damage was at soft-soil sites, and it was typically to nearly full tanks. Unanchored tanks with height to diameter ratio exceeding 0.5 were especially vulnerable (EERI, 1990).

3.2.4 Failure Mechanisms

The most characteristic type of liquid storage tank damage is a circumferential "elephant's foot" bulge that can form near the base of the tank due to excessive compressive loads in the tank wall (Nyman and Kennedy, 1987,EERI, 1986, Haroun, 1983). Excessive sloshing of tank contents has often resulted in damage to floating and fixed roofs, and tank settling, sliding, or rocking has caused breakage or pull-out at piping connections. Differential settlements of the foundation have also led to tank failure.

In the 1989 Loma Prieta earthquake, damage to unanchored tanks was associated with uplift of the tank walls. Uplift displacements between the shells and foundations of some fully loaded tanks was judged to be between 150 and 200mm (6 and 8in). Failure types included elephant's foot buckle, vertical splits in tank walls, ruptures of elephant's foot buckles, puncture of tanks by restrained pipe, and damage to restrained piping anchored to both tank and foundation (EERI, 1990). Similar, partially filled or empty tanks, adjacent to the damaged ones, were undamaged. During the 1952 Kern County earthquakes, oil-storage tanks were occasionally damaged near their tops by sloshing oil. Floating tops suffered more damage than fixed roofs (ASCE, 1987).

A major oil refinery with about 90 storage tanks in the area of the 1978 Sendai earthquake had three large tanks fail and three others damaged without failure. Bolts around the circumference of a large welded steel-plate water tank were pulled out of their concrete embedment from 25 to 150 mm (1 to 6 in). There was no damage to the base of the tank. Several LPG tanks at the refinery suffered only minor cracks in concrete supports. These tanks were heavily braced with diagonal braces having circular cross sections (EERI, 1986).

Only one of six unanchored ground-based tanks which were 99 percent full was damaged by the 1975 Imperial Valley earthquake. The largest one was damaged and spilled oil. Failure of the fixed steel-plate roof and separation of the perimeter weld around the roof allowed some of the sloshing oil to run down the exterior of the tanks. Four of 18 gasoline and diesel tanks at a tank farm suffered damage in the form of a moderate elephant's-foot bulge. There was no apparent leakage. The tanks were located on concrete ring walls or compacted gravel fill, none were anchored, and most had floating roofs. Compression buckles were more prominent in tanks supported on concrete ring walls than those on gravel fill (EERI, 1986).

Of the 120 vertical unanchored tanks at a refinery, 12 were damaged during the 1985 Chile earthquake. The tanks had capacities between 2,500 and 125,000 barrels. Most tanks appeared to have failed either at the base plate or at the weld between the wall and base plate. Several elephant's foot buckles were observed, and at least four tanks had roof damage when their contents emptied faster than relief valves equilibrated the pressure. Damaged tanks were either full or nearly full at the time of the earthquake. Many of the tanks appeared to have rocked, and differential settlement damaged the pipes exiting some of the tanks at their bases (EERI, 1986).

Many tanks were affected by the 1971 San Fernando earthquake. Damage to two water tanks was reported (EERI, 1986). One of them was a large tank about three-fourths full which showed signs of having rocked on its foundation. Some of the anchor bolts failed in tension and others apparently failed in bond and were pulled up out of their anchorage from

50mm (2in) on one side to 356mm (14in) on the other side. The other tank sustained an outward bulge close to ground level almost all the way around the circumference (elephants-foot buckle). The bulge covered a height of about 508mm (20in) and an amplitude of about 200mm (8in). The outlet pipe and connection broke, the floor plate broke from the walls at one place, and water emptied.

Damage to elevated tanks was reported to fall in the following categories: damage to the support structures, such as stretching of ties, buckling of struts, tearing, warping, and rupture of gusset plates at end connections; separation of clevises, rivets, and bolts; damage to piping and other appurtenances connected to tanks due to tank movement; damage to anchor bolts; damage to the foundation system,which was aggravated in some instances by liquefaction and slope failures (EERI, 1986).

Two elevated tanks were reported to have received minor to moderate damage during the 1979 Imperial Valley earthquake, and a 380,000L (100,000 gal) water tank collapsed. This tank was estimated to be 30m (100 ft) high by 9m (30 ft) at the base and it had four tubular legs braced with tiers of diagonal rods (EERI, 1986).

3.2.5 Design Methodologies

Manos and Clough, 1983, state that there is a need for a realistic prediction of the uplift mechanism and the out-of-round distortional response to be incorporated in the design of tanks, and that foundation flexibility should be considered in the design of free and fixed base tanks. Combra, 1983, notes that there is a need for a new theory concerning tank resistance to lateral force. Haroun and Tayel, 1983, state that with few exceptions, current seismic design codes for ground-base cylindrical tanks neglect the effect of vertical ground accelerations. Research and analyses of storage tanks with regard to their response to earthquakes are reported by Shibata et al., 1983.

3.2.6 Lessons Learned

The Earthquake Engineering Research Institute concluded that the following lessons can be learned from the performance of gas and oil storage tanks in past earthquakes (EERI, 1986):

- Much of the poor earthquake performance of tanks can be attributed to the fact that unpressurized tanks, though structurally very efficient for vertical gravity loads, are not structurally efficient for lateral earthquake forces.

- The performance of anchor bolts at tank bases and towers has been poor in many cases. Anchor bolt failure during many seismic events shows that more thought must be given to their use and detailing, and to whether bolts are needed.

- Enough freeboard must be provided to prevent waves from contacting the roof system. In many cases, insufficient freeboard has led to damage of roofs by sloshing liquid.

- Flexible joints or adequate piping flexibility that allows for expected relative motion between tanks and piping should be used. The failure of rigidly attached piping often causes tank contents to be released.

- Because damage to elevated tanks affects the supporting structures while the vessel remains intact, better design of the struts and detailing of the connections is required.

3.3 Structures and Above Ground Support Facilities

3.3.1 Overall Performance Record

Control systems and communications are critical for safe and continuous operation of gas and liquid fuel pipeline systems and are vital for emergency response. Observations after the 1987 Ecuador earthquakes (Crespo, O'Rourke, and Nyman, 1988) suggest that these facilities need more attention. At the Salado Pump Station in Ecuador, control panels were damaged, the main control valve was buried and jammed in an open position by landslide debris, electrical power and auxiliary generators were out, and the radio communications antenna had buckled and become inoperable. At most facilities, control and communication systems have been procured and installed without regard to earthquake resistance, and outside California, anchorage of these critical items has often been inadequate or nonexistent (Nyman, 1991).

Many of the support facilities are similar to other industrial facilities. The major difficulty in evaluating seismic performance of industrial facilities results from their diverse geographical locations, special design considerations, different dates of construction, and from the fact that criteria for seismic design vary from structure to structure (EERI, 1986). It is well known, that port and harbor facilities, including piers, docks, quays, and landings, are particularly susceptible to the effects of strong earthquakes (EERI, 1986).

Experience indicates that modern facilities designed and constructed in accordance with modern United States seismic practice, with particular attention given to adequate anchorage of equipment, can be expected to sustain no significant loss of operating function when subjected to high-level resonant ground motion (ASCE, 1984). The components of oil and gas pipeline systems which satisfy modern seismic design criteria, have in general exhibited good behavior in past earthquakes. This includes the above ground components such as compressor stations, pumping stations, and control stations (ASCE, 1984, EERI, 1986). Proper anchorage of equipment, including items in the control center, can greatly reduce damage and minimize injury to personnel (EERI, 1986).

Four major modern industrial facilities subjected to severe ground motions during the 1985 Chile earthquake performed well, although minor damage was sustained, none of these facilities were shut down (EERI, 1986). Industrial facilities in general were also not seriously damaged by the 1989 Loma Prieta earthquake.

Limited information is available pertaining to pipeline stations and terminal facilities, however there is considerable information available on the performance of similar facilities which include refineries and power plants. Experience has shown that the seismic performance of large equipment and machinery is vital and the most important design consideration is providing adequate anchorage (Nyman and Kennedy, 1987, ASCE, 1984, ASCE, 1974, EERI, 1986, Anderson, 1985).

It has been found from pipeline projects that critical electrical equipment and instrumentation which includes computers, valves, motors, control panels, and pressure switches exhibit good resistance to seismic shaking when securely anchored. Lack of anchorage or inadequate anchorage of equipment has led to rupture of electrical connections and thus failure of electrical power supply (Nyman, 1987, ASCE, 1984, EERI, 1986).

Bettinger, 1980, reported that limited experience with gas compressor stations in earthquakes has been favorable. Gas compressor stations are conservatively designed and built, and further provisions for seismic resistance do not appear to be warranted.

Schiff and Yanev, 1989, reported on damage caused by the 1989 Armenian earthquake to two non-nuclear power facilities. They noted that equipment anchorage could be improved.

Underground facilities such as vaults and manholes were not damaged structurally as a result of the 1971 San Fernando earthquake. This was true for cast in place and prefabricated vaults (ASCE, 1974).

3.3.2 Design Methodologies

Current design practices recognize that equipment outages due to earthquakes can best be mitigated by proper design provisions to prevent sliding or tipping of equipment and falling debris (Anderson, 1985). Mechanical and electrical equipment and instrumentation serving pipeline transmission systems can be vital for maintenance of a sufficient level of service and for control and emergency procedures in the event that damage occurs.

For critical equipment and instrumentation, a seismic qualification procedure may be implemented to demonstrate the capability for continued or uninterrupted operation (Nyman, 1987, Anderson, 1985, Anderson and Nyman, 1979, 1977). Seismic qualification has been of great importance for many years in nuclear power plants. A useful guide for seismic qualification can be gained from examining the performance of equipment and instrumentation during previous destructive earthquakes.

EERI, 1986 reported that the state of practice of earthquake resistant design of industrial buildings needs to be improved in some areas. The level of damage has been significant, even to modern structures, during some recent moderate earthquakes. Foundation performance contributed to some of the problems, but most of the damage was a direct result of poor connections and inadequate anchorage.

3.3.3 Lessons Learned

The Earthquake Engineering Research Institute concluded that the following lessons can be learned from the performance of gas and oil storage tanks in past earthquakes (EERI, 1986):

- The information available suggests that above-ground facilities that are designed to resist seismic effects suffer limited damage in earthquakes.

- Proper anchorage is important in preventing damage to mechanical equipment. When outages occur as a result of an earthquake, the cause can usually be traced to falling debris, collision with other items, sliding (with subsequent rupture of electrical connections or piping), or failure of the electrical supply.

4. AVAILABLE DESIGN CRITERIA,REMEDIAL MEASURES, STANDARDS, AND DESIGN GUIDES

4.1 Introduction

This section addresses the design of new systems, as well as the retrofitting of existing systems. Three levels of sophistication are identified. State of the art methodology is at the highest level. At this level, engineers can design a pipeline or storage tank using the latest methodologies in site exploration and mathematical modeling, reflecting our present state of knowledge. For very large and important projects, such as the Trans-Alaskan Pipeline, this has been done, and the only question that arises is whether the present state of knowledge is adequate. At the second level are established design criteria and methodologies. At the third level are standards, codes and design provisions which can be made mandatory and thereby establish a minimum level of performance. It is the third level which is of greatest interest in this report, because it is important to determine whether existing standards, codes or design provisions, when minimally complied with, will produce systems which will perform adequately. However, it is also important to establish whether the present state of knowledge is adequate.

In addition to a discussion of the topics, relevant information from the technical literature is presented. The views expressed in this latter information, which is typed in italics, are not necessarily consistent with those expressed by the authors of this report.

4.2 Design Criteria

4.2.1 Development of Design Criteria

The development of seismic design criteria first became of real interest to the petroleum industry following the damage to oil storage facilities during the 1933 Long Beach, California earthquake. Development of seismic design criteria for critical facilities occurred relatively slowly until about 1960 when the advent of nuclear power plants triggered the need for developing and employing modern earthquake engineering principles and practices.

Following the 1971 San Fernando earthquake, interest in the effects of earthquakes on lifeline systems appreciably increased. In 1974 the American Society of Civil Engineers formed the Technical Council on Lifeline Earthquake Engineering (TCLEE). Since that time there has been an increasing number of technical papers on the subject.

Seismic design procedures for gas and liquid fuel pipelines were proposed by Kennedy et al., 1977, Hall and Newmark, 1977 and Hall and Kennedy, 1980. By 1984 the Gas and Liquid Fuel Lifelines Committee of TCLEE developed "Guidelines for the Seismic Design of Oil and Gas Pipeline Systems" (ASCE, 1984).

The ASCE "Guidelines for the Seismic Design of Oil and Gas Pipeline Systems" (1984) are intended primarily for engineers engaged in the design of most major components of gas and liquid fuel pipeline systems. The document also provides guidance to pipeline company management, disaster recovery agencies, regulatory agencies, and insurance groups. The document provides general guidance on design, construction, operation, maintenance, and upgrading of systems and components common to pipeline systems.

Hall, 1987, reported that considerable additional work can be done to reduce damage to pipelines and facilities when subjected to moderately severe earthquakes. Improvements in earthquake engineering center around sound engineering practice that can be attained only if there is a good understanding of the expected behavior of pipelines and related facilities.

4.2.2 Current Design Criteria

4.2.2.1 Pipelines

As noted in Section 3, modern continuously-welded ductile steel pipelines performed well in past earthquakes. However, even with modern ductile pipelines, there are problems in areas of severe soil deformations, at connections to structures, at locations of bends and junctions, and at locations where pipelines are threatened by failures of bridges, dams, and electrical systems, or by earthquake related phenomena such as landslides, tsunamis, seiches, and soil liquefaction.

Thus there is a need for seismic provisions which promote good construction and quality control. The most important aspect of such provisions should be proper siting, designed to avoid hazardous conditions. It is important to recognize that some damage under severe conditions should be anticipated even in pipelines which were designed to be earthquake resistant. Thus, there is also a need for monitoring and emergency shutdown systems which will minimize the environmental and economic consequences of pipeline failures. Analytical, laboratory, and field studies of performance of gas and liquid fuel pipelines should be conducted to develop improved design, assessment and retrofit practices.

Important aspects of pipeline design as discussed in the current technical literature are presented below:

> *Nationally applicable design and construction provisions for new lifelines, and strengthening provisions for existing lifelines should be developed. In contrast to buildings, and except for highway structures, no nationally applicable design and construction practices are available for new and existing lifelines (NIST, 1990). Eguchi, 1987, reported that with the exception of the Trans-Alaskan Pipeline, very little has been done in the area of system and component performance criteria development for oil and natural gas pipeline systems. The primary reason for the lack of criteria is that requirements tend to differ from one system to another, thus influencing the level of performance.*

Many studies, analyses and recommendations were made following the 1971 San Fernando earthquake. It was concluded that there does not appear to be an economical method for fully preventing damage to underground lines due to extreme differential ground movements (Nyman, 1987,Johnson, 1983). Eguchi,1987, reported that the majority of oil and natural gas pipeline system components in the United States are highly vulnerable to earthquakes either because newer seismic design procedures have not been applied at the appropriate level or because of the severity of hazards in the areas they occupy have not been adequately assessed.

The seismic design criteria formulated for each of the pipeline system components should provide estimates, and the basis for such estimates of forces, ground movements or other vibratory motion effects that would be expected for a postulated design earthquake (ASCE, 1984). Most pipeline systems, especially in regions of high seismic exposure, are subject to restrictions and performance requirements of federal and state governmental regulatory agencies as well as those of the facility owner (ASCE, 1984). The pipeline as well as pumps, compressors, flow monitoring and control equipment and other parts of a facility which are critical for continued operation and system control normally should be designed to service a major earthquake with almost no damage. However, structures housing this equipment, storage buildings and other structures not directly affecting the operation of a pipeline facility could experience large inelastic deformations provided possible interaction between the structure and enclosed components does not compromise safety or the operation of critical components of the facility ASCE, 1984).

Pipeline steels generally can accommodate average tensile strains on the order of 2 to 5 percent without rupture, with local strains of 15 percent or more. In Japan, steel pipes are allowed to have a design strain of 0.3% for a rare earthquake (Singhal, 1983-III). A reasonable criterion, suggested by Hall and Newmark, 1978, for permissible deformation to avoid rupture appears to be in the order of 1% to 2% strain in modern steel pipe at any section. Careful quality control over pipeline manufacture and welding is required for achieving the desired performance under these strains (Nyman and Kennedy, 1987).

For optimal design of gas transmission networks, the following design variables need to be determined: number of compressor stations, compressor station locations, lengths of pipeline segments between compressor stations, diameters of pipeline segments, and suction and discharge pressures at each compressor station (Edgar et al., 1978). Damage to pipelines may be minimized provided that a correct choice of pipe material, type of joints, arrangement of the network, length of segments, location and details of fittings and accessories are made, and as long as pipelines are not located in the vicinity of fault or landslide zones (Fu-Lu, 1983).

Under extreme earthquake conditions, it is reasonable to permit larger movements for pipelines, except at restraints such as anchors, valves or pump stations, than for plant facilities (Darragh, 1983). Experimental studies have been conducted on the mechanical behavior of PVC pipelines subjected to ground subsidence (Takada, 1983).

4.2.2.2 Storage Tanks

Many storage tank failures have been caused by earthquakes. Thus, the need for special seismic design provisions is generally recognized. Such provisions require consideration of anticipated lateral and vertical forces. Criteria for estimating anticipated earthquake effects have been developed (Wozniak and Mitchell, 1978), and were incorporated in existing standards (API 650, AWWA D 100). In addition to consideration of inertial forces, design criteria should also deal with preferential tank geometry (tanks with large fluid depth to diameter ratio are particularly vulnerable), siting, and secondary containment to minimize the effects of potential spills. Defensive siting and secondary containment are required for LNG tanks, but not specifically mentioned in design provisions for other fuel storage tanks. As in the case of pipelines, the most important aspect of seismic design is defensive siting, which avoids potential liquefaction hazards and sites where the ground motion is amplified, as well as sites subjected to tsunamis, seiches, other types of flooding, landslides and ground rupture. Unlike transmission pipelines and distribution piping networks, storage tanks in most instances can be located to avoid special site hazards.

Design criteria for above-ground tanks are provided in ASCE, 1984, API 650, AWWA D 100, and for buried tanks in Army Manual TM 5-809-10-1, "Seismic Design Guidelines for Essential Buildings". Haroun, 1990, discusses the API 650 and AWWA D 100 design procedures. The seismic loads in these two most commonly used standards for tank design are based on a mechanical model derived by Housner, 1957, for rigid tanks. Recent versions of the standards have adopted an increase in the acceleration coefficient, which represents the short-period amplified acceleration due to shell deformation. This value of acceleration coefficient, in general, is specified independently of the tank dimensions and support condition. The lateral base shear force is determined from a number of coefficients for site location, natural period and soil profile. For such computations, the input requirements consist of a zone coefficient, a site factor, the response period, and the effective masses and their elevations.

The use of a response spectrum is encouraged by the AWWA standard for sites that might experience severe ground motion during the life of the structure. When the response spectrum is selected, the accelerations obtained from the spectrum are substituted for the seismic coefficients. The API 650 AWWA D 100 standards use somewhat different methods for determining seismic coefficients. In the API standard, the specified seismic coefficient is multiplied by an importance factor to obtain an effective seismic coefficient, whereas in the AWWA standard, the effective seismic coefficient is determined by multiplying a set coefficient by a "structure coefficient" which is different for anchored and unanchored tanks. The computation of forces due to convective motion of fluid is also slightly different in the two standards.

The bending moment at the shell base is used for evaluating the compressive and tensile forces in the tank shell. The allowable earthquake compressive stress consists of the static allowable stress plus a stabilizing stress due to the internal liquid pressure with the sum increased by a specified amount. The stabilizing stress depends on geometric terms and a pressure stabilizing coefficient. Overturning moments, including those arising from the pressure variations on the base, are computed for the design of the foundation.

Other important aspects of storage tank design as discussed in the current literature are presented below:

> *Manos and Clough, 1983, state that there is a need for a realistic prediction of the uplift mechanism and the out-of-round distortional response to be incorporated in the design of tanks, and Combra, 1983, notes that there is a need for a new theory concerning tank resistance to lateral force. Foundation flexibility is another factor that should be considered in the design of free and fixed base tanks (Manos and Clough, 1983). Research and analyses of storage tanks with regard to their response to earthquakes are reported by Shibata et al., 1983. With few exceptions, current seismic design codes for ground-based cylindrical tanks neglect the effect*

of vertical ground acceleration (Haroun and Tayel, 1983).A better understanding of the behavior of unanchored tanks, an assessment of the effect of the vertical component of ground motion on tank response, and an acceptable estimation of shell strength against buckling are needed (EERI, 1986).

4.2.2.3 Structures and Support Facilities

Design criteria for structures are well defined and reference to various existing standards can be made for design direction and appropriate formulations (e.i., NEHRP Recommended Provisions; BSSC, 1988; SEAOC, 1987; UBC; BOCA). Most regions in the country legally adopted seismic design standards for buildings. However these provisions may not be sufficient for industrial type facilities. Seismic design provisions for support facilities are also available (Anderson, 1985). The most important aspect of these provisions is to provide resistance to tipping, sliding and uplift. The equipment itself, such as pumps and compressors, does not seem to be particularly vulnerable to earthquake shaking. Nevertheless, it has been suggested that a seismic qualification procedure for peripheral equipment, similar to that used for nuclear power plant equipment, could provide the capability for uninterrupted operation of the transmission system.

Important aspects of design practices as discussed in the current technical literature are presented below:

Ground shaking is a major design factor for pump stations and marine terminal facilities, tank farms, above ground sections of pipeline and above ground structures in general. The effects of tsunamis or seiches often must be incorporated in the site selection and design of marine terminal facilities (ASCE, 1984).

Current practices recognize that equipment outages due to earthquakes can best be mitigated by proper design provisions to prevent sliding or tipping of equipment and falling debris (Anderson, 1985).. For critical equipment and instrumentation, a seismic qualification procedure may be implemented to demonstrate the capability for continued or uninterrupted operation (Nyman, 1987, Anderson, 1985, Anderson and Nyman, 1979, 1977). Seismic qualification has been of great importance for many years in nuclear power plants. A useful guide for seismic qualification can be gained from examining the performance of equipment and instrumentation during previous destructive earthquakes.

It was reported by EERI (1986) that the state of practice of earthquake resistant design of industrial buildings needs to be improved. The level of damage has been significant, even to modern structures, during some recent moderate earthquakes. Foundation performance contributed to some of the problems, but most of the damage was a direct result of poor connections and inadequate anchorage (EERI, 1986).

4.3 Emergency Response, Evaluation, Repair and Retrofitting

4.3.1 Emergency Response

The previous section deals with the design of new fuel pipeline systems and their components. However, most of the risk is associated with existing systems which were not designed to be earthquake resistant. For such systems it is important to have contingency plans to deal with various types of anticipated earthquake damage and monitoring systems which will provide information in case of earthquake damage.

The major West Coast pipeline companies have in general included earthquake planning in their emergency procedures. There are cooperative agreements among a number of major companies to share their resources in the event of a major emergency such as an earthquake. The emergency plans appear according to Nyman, 1987, to be a model for utilities in other seismic risk areas such as the New Madrid area and the East Coast.

Recommendations for land use measures are of interest. Recent laws in California call for seismic hazards mapping, such as the Alquist Priolo Act (fault zones) and the Seismic Hazards Mapping Act of 1990 (liquefaction, landslides, and site amplification). They are designed to identify zones of increased risk from large permanent and transient movements. Given the co-existence of critical gas and liquid fuel lifelines and statutory zones of ground failure hazards, it can readily be anticipated that land use planning will play an important role in future measures to curb earthquake risk to lifeline systems.

Emergency response practices depend on emergency planning and preparedness. The National Transportation Safety Board (NSTB) has questioned the adequacy of measures taken to protect public safety near pipelines. Their interest is in more effective land use planning and policies, damage prevention, and in more responsive emergency preparedness programs (TRB, 1988). Thus, plans for improvements in seismic resistant practices should be coordinated with current recommendations for enhancing general practices for pipeline safety, such as those presented by the Committee for Pipelines and Public Safety of the Transportation Research Board (TRB, 1988).

Summarized below are observations on these problems taken from the current technical literature:

> *Seismic risk assessment methods for natural gas and oil pipeline systems discussed by Eguchi, 1987, allow natural gas utilities and oil companies to better understand the weaknesses of their system and thus understand where to concentrate most mitigation or response planning efforts. The results of studies by several major gas utility companies in California are being used to: (1) identify vulnerable pipeline elements, (2) estimate probable service levels after a major earthquake, and (3) test current emergency response plans (Eguchi, 1987). Eguchi, 1987, described a seismic risk methodology for natural gas and oil systems intended to identify weak links within a system, establish minimum performance standards for facilities, assess minimum performance for the system with regard to an earthquake, test various mitigation, retrofit, and/or design strategies, and to test emergency response plans.*
>
> *Past earthquake fires in Japan have led to installation of peak acceleration detectors at various locations in gas transmission lines (Schiff et al., 1984). Detection of certain levels of peak acceleration will reduce the pressure in the lines and isolate LPG storage tanks. Higher detected levels of acceleration will stop gas generation and valves to the transmission are closed so that the system is sectionalized. Very high accelerations will result in purging of gas transmission lines. It is noted that in 1973 McNorgan stated that the installation of earthquake, vibration, or automatic shut-off valves is not a panacea for such situations, unless an individual is capable of determining the where and when of earthquakes. Installation of such valves could cause more problems from an operational standpoint than they might solve (McNorgan, 1973).*
>
> *Japan has had experience with post-earthquake operation of gas systems. Many storage facilities required strengthening. Special criteria for their strengthening were developed (Schiff et al., 1984).*

4.3.2 Evaluation

To determine whether fuel transmission systems should be protected against earthquake effects by retrofitting, it is important to evaluate their condition and assess their damage potential. Another problem is evaluation after an earthquake has occurred. In the case of buried pipelines this poses a difficult problem because they are not directly accessible for inspection. The problem is compounded by the fact that pipelines may have sustained damage which requires repair even if they continue to function normally.

Hale, 1984, notes that internal pipe inspection can be carried out by (1) visual (closed circuit television or conventional film camera), (2) electromagnetic, and (3) ultrasonic procedures. It is noted that a closed-circuit TV system is available for piping systems down to 1 1/2 in (40-mm) diameter. Electromagnetic devices have been used to inspect more than 100,000 miles (160,000 km) of pipelines and gas distribution lines from 4 to 48-in (100 to 1220-mm) diameter over the last 20 years. Newly developed on-line inspection vehicles can pinpoint flaws to within a few feet, locate significant defects, and make automatic analysis of data without interfering with pipeline operation.

Summarized below are other observations on these problems taken from the current technical literature:

> *Eguchi, 1987, stated that one of the most critical problems faced by oil and natural gas pipeline operators after a major earthquake is the immediate detection and isolation of damage to the system. Currently (1987) no system or methodology exists for early damage detection of lifelines following an earthquake.*
>
> *Quantitative models for identifying earthquake damages to pipelines have only recently been developed. Those models available still do not satisfy prediction needs entirely (ATC, 1985). A methodology to perform seismic hazard analysis of geographically extensive regions has also been presented (Monzon-Despang and Shah, 1983).*

4.3.3 Repair

Buried pipelines can be severely deformed by ground distortions which may or may not lead to failure. Current practice according to Nyman, 1987, calls for cutting out and replacing sections of pipelines that have experienced deformations and have been determined to be unacceptable for safe operation. An account of repairs to a natural gas distribution system with some information about a transmission pipeline system is given by Johnson, 1983.

4.3.4 Retrofitting

Retrofitting is necessary to update equipment for more efficient and economic operation and in a form to preclude damage in an earthquake (Hall, 1987). Renovation of existing piping involves rebuilding or restructuring so that it will provide many more years of service without removing the buried pipe and replacing it with new piping material (Hale, 1984). Considering the amount of cast iron gas mains still in existence and operation, plus a growing mileage of aging steel mains with corrosion problems, a substantial need exists for the renovation of current pipeline systems.

Hale, 1984, has reported on renovation techniques currently used by distribution companies for improving the performance of aging mains, particularly those composed of cast iron and corroded sections of steel. Some of these renovation techniques also qualify as measures to improve seismic performance by enhancing the strength and continuity of the piping. Renovation techniques, which can improve seismic performance, include external encapsulation of joints and fittings (generally with a molded polyurethane fitting), insert renewals with plastic pipe, and pressure relining of pipelines with plastic pipe.

In situ cleaning and coating of oil and gas pipelines have gained popularity as operators discover that it is much less costly to renovate troublesome lines than to replace them (Hale, 1984).

To minimize damage from earthquakes, either actual or potential, a rigorous continuing inspection and maintenance program is required (ASCE, 1984). Inspection and maintenance programs should, in general, consist of (1) as-built documentation, (2) inspection plans which include any needed measurements and their frequency, and (3) maintenance and repair plans. The as-built documentation is important so that any differences from design or design assumptions are recognized, documented, and evaluated for their effect on seismic performance. The inspection plan should include a recognition of those key components of seismic design which are required to ensure the design integrity and a scheme for monitoring those components. Measurement programs vary from accurate location of reference monuments pertaining to pipeline system routes and components and ground movement detection devices, to installation and reading of strain gages and other measuring instrumentation. Monitoring frequency should be scheduled to permit early detection of changes in field conditions or in the condition of the facilities which could increase the exposure to seismic hazards. The repair plan depends on anomalies uncovered in the inspections and also includes recognition of recurring problems which have been periodically corrected along with standard corrective actions implemented by operating personnel.

Potentially unstable slopes in the vicinity of the pipeline route should be inspected periodically to determine whether changes have occurred in the field which could change drainage patterns. Another important inspection and maintenance activity often overlooked is the identification of vulnerability to non-structural damage caused by the overturning of unanchored equipment, furniture, and storage racks. These unanchored items should not be allowed to move or overturn so that adjacent critical components are damaged or otherwise rendered nonfunctional (ASCE, 1984).

Consideration should be given to the proper storage of repair parts, tools, and equipment so that during an earthquake they are not damaged or cause injury to workers. These items need to be readily available and usable following an earthquake.

Most pipeline systems experience upgrading or replacement during their operational life. Care should be taken to ensure that changes to the facilities and components satisfy the original or updated seismic criteria and specifications (ASCE, 1984).